Accelerating Muons
Options and R&D

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NuFact 06
27 August 2006

Challenges of Accelerating Muons

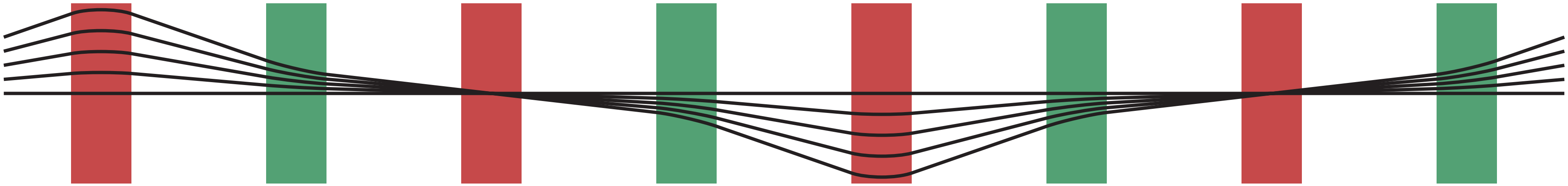
- Primarily talking about neutrino factories, some comments on muon colliders
- Muons decay: must accelerate rapidly
- Muon beam sizes are large
  - Beam can be made smaller by ionization cooling
    - Ionization cooling is expensive: do as little as needed
    - Creating very small beam sizes is technically challenging
  - Large transverse beam sizes
    - Magnet apertures large
    - Smaller for muon colliders: more cooling
  - Large energy spreads (longitudinal beam sizes)
    - Still large for muon collider
  - Forced to low frequency RF (200 MHz or lower)

Simple Solution: Linac

- Why not just use a linac?
- Low frequency, large aperture means linac is very expensive
  - Most of the cost is in the RF accelerating systems
  - Thus, less costly solutions will make multiple passes through the RF
    - To lowest order, the number of passes through the RF is the standard by which we judge accelerating systems

Linac
Time of Flight and Transverse Amplitude

- Technical problem (comes up again later): time of flight depends on transverse amplitude
- Larger transverse amplitude, longer path for particle trajectory
- Large transverse beam sizes, high amplitude particles are no longer on RF crest
- Except for very low energies, no synchrotron oscillations
  - Synchrotron oscillations swap late and early particles
  - Desirable to introduce synchrotron oscillations



Recirculating Linear Accelerators (RLAs)

- Make multiple passes through linacs, connecting them with arcs
- After each linac pass, beam goes through a different arc
  - Switching between arcs limits number of turns
    - Finite beam size and energy spread, cannot overlap different passes
    - Need space between magnets for different passes (coils!)
  - Turns limited in practice to 5 or so

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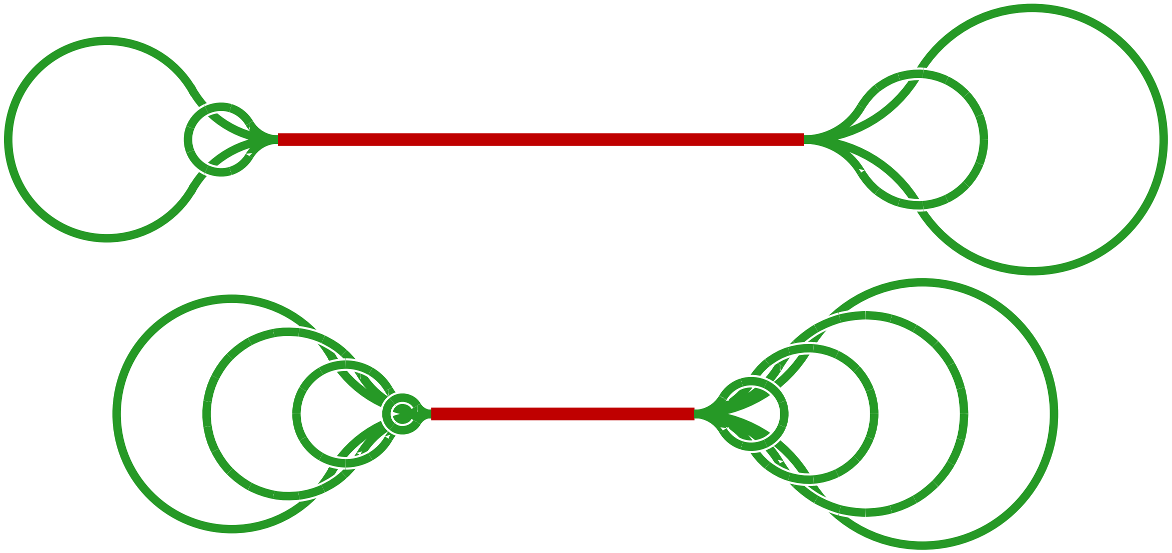
Dogbone RLA

- Can change the geometry of the RLA for improved efficiency
  - For same total amount of linac, more separation at switchyard
  - For same switchyard, smaller amount of linac (double passes!)
- More complicated lattice
  - Requires vertical bending: crossing arcs
  - Two bending directions adds complication



Fixed Field Alternating Gradient Accelerators (FFAGs)

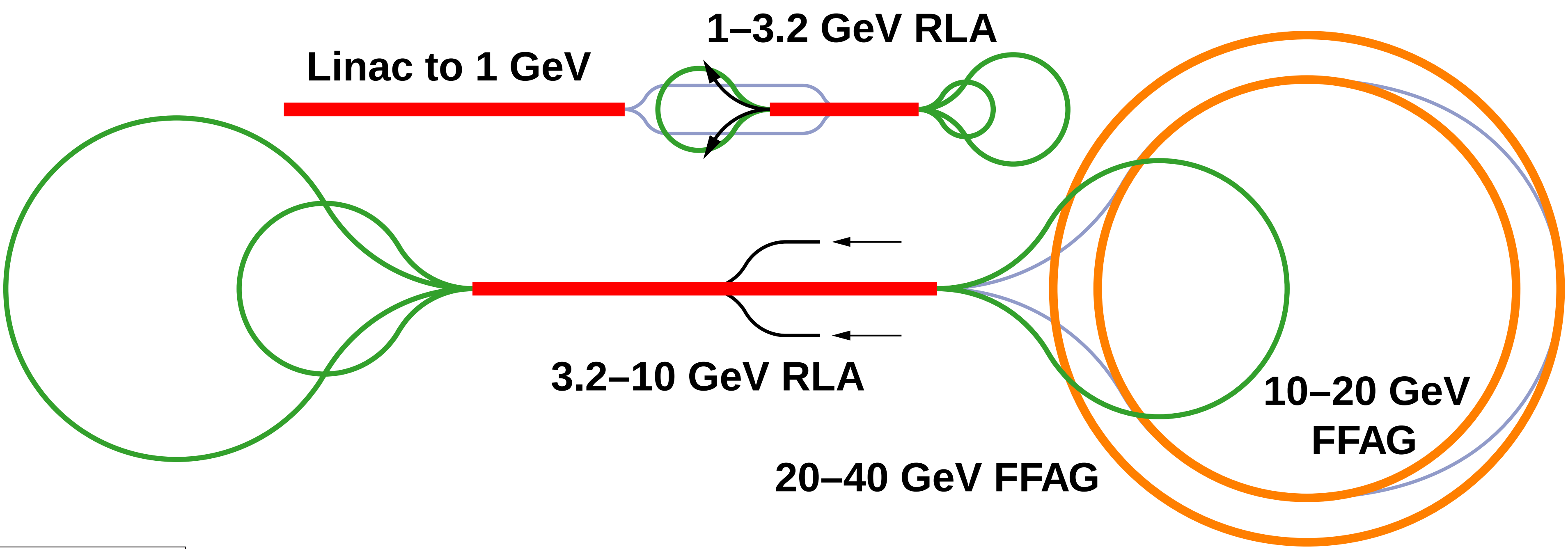
- To get more turns, eliminate the switchyard
  - Eliminate the separate arcs
- Make an arc which accepts a factor of 2 or more in energy: FFAG
  - Circular ring, RF cavities distributed around the ring
- Potentially allows many more passes through the RF

FFAGs
Limitations to Number of Turns

- Maintain high field gradient
  - Bending field determines circumference
  - Number of turns determined by gradient and energy range
- Cannot replenish stored energy in cavities between turns
  - Can’t extract too much stored energy
  - Limits number of passes through RF
- Can’t control revolution time for each pass
  - Particles won’t stay on the RF crest
  - More passes, get further off crest
- In general, more efficient at higher energy

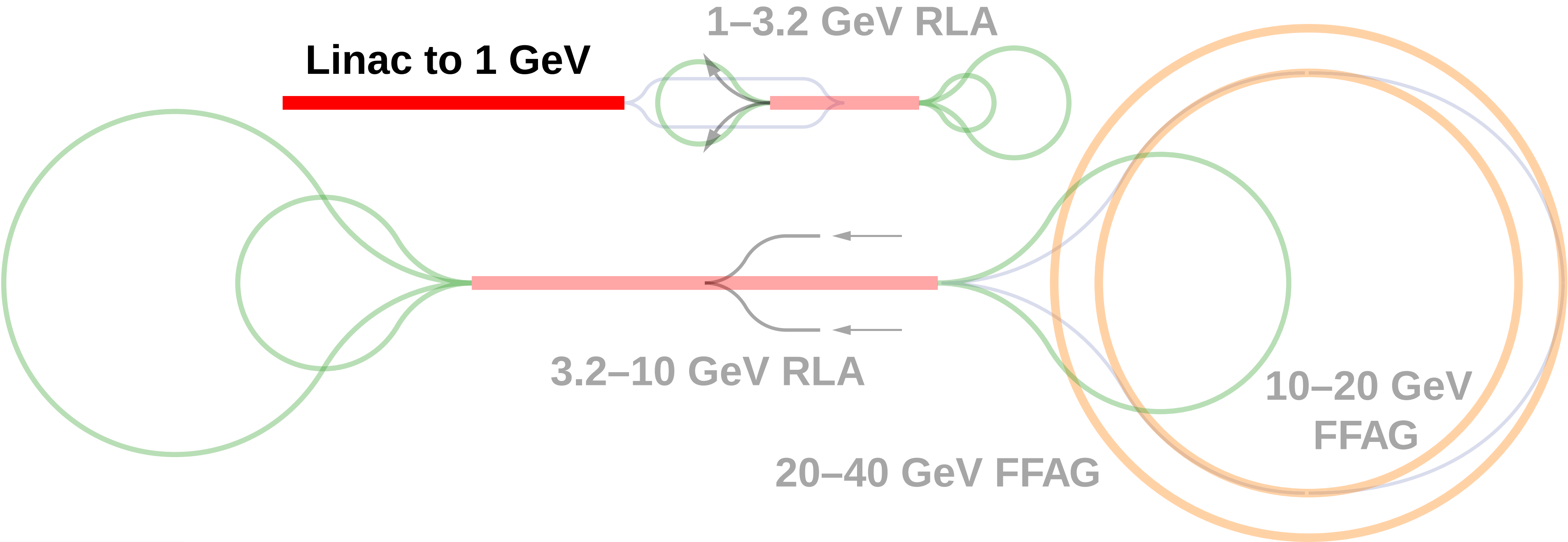
Full Neutrino Factory Acceleration System

- Acceleration involves all the systems described above
- Which system to use at what energies determined by cost
  - Strongly related to number of passes through RF



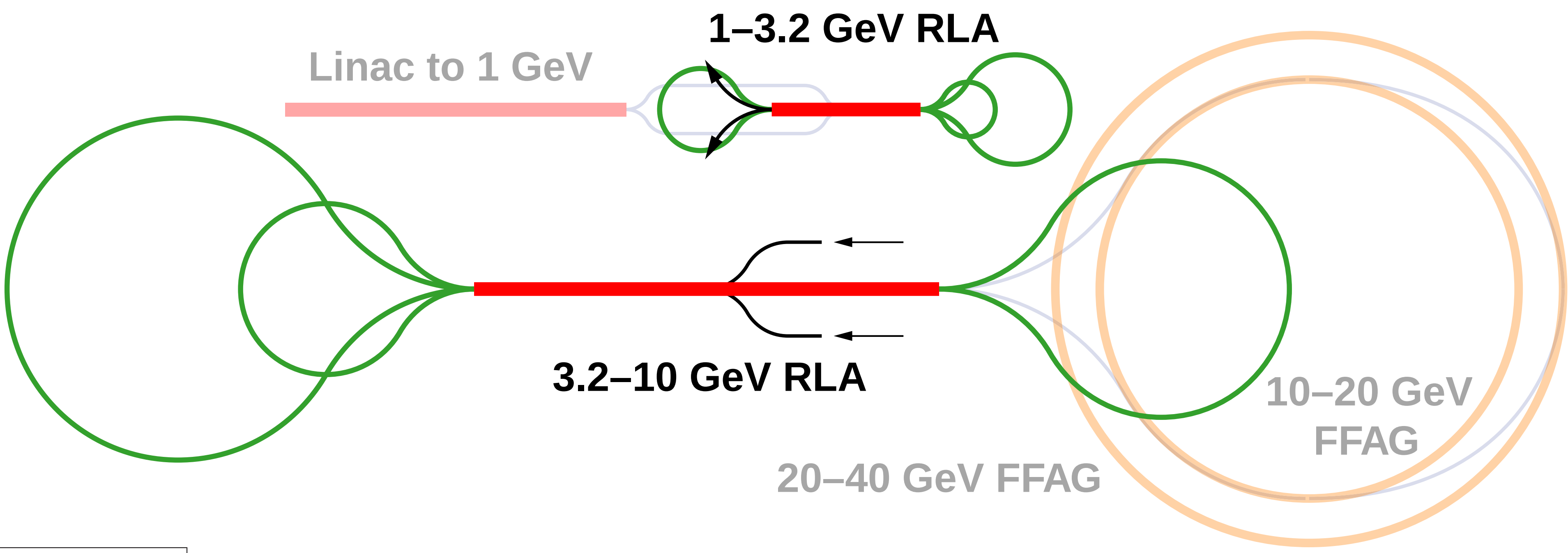
Full Acceleration System
Linac

- RLAs have difficulty with low energy
  - Velocity difference between linac passes
  - Large beam size
- RLA stage works best with a modest factor in energy increase
- Low energy thus most efficiently done with a linac



Full Acceleration System
RLAs

- Use RLAs for lower energies until FFAGs become more efficient



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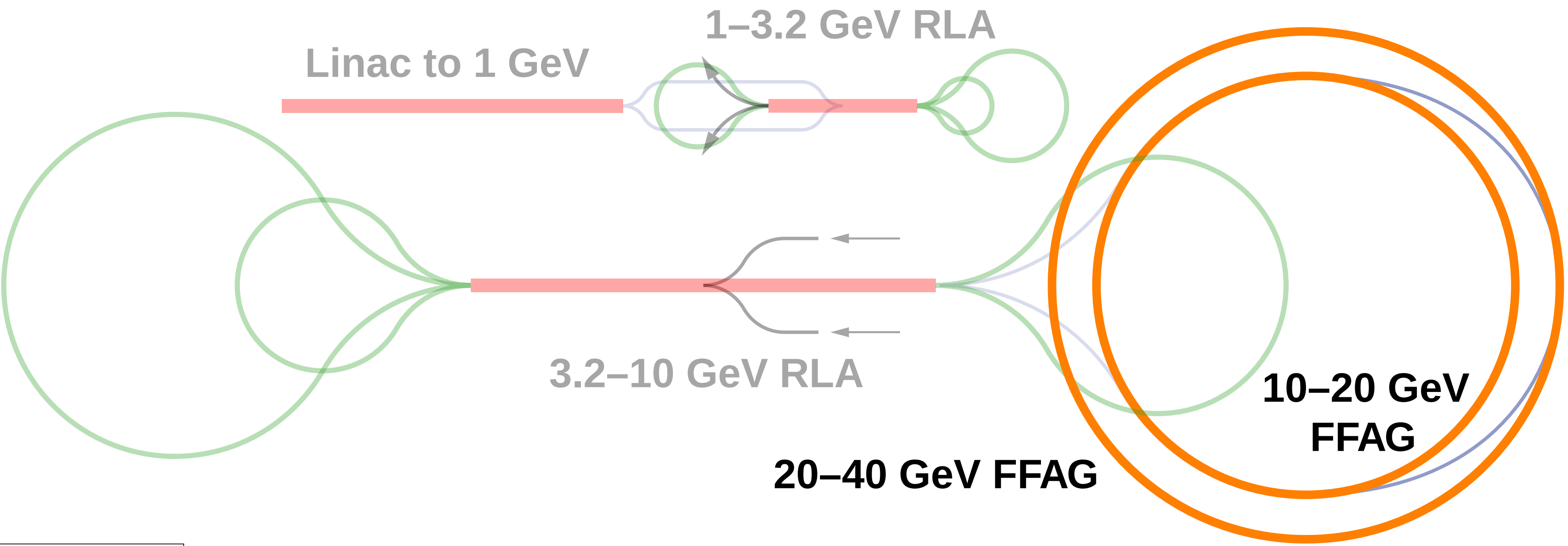
Full Acceleration System
FFAGs

- Use FFAGs once the energy is high enough for them to be more efficient than RLAs



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Muon Colliders

- Above systems were for neutrino factory
- Muon collider acceleration system will have to start similarly
  - Large longitudinal emittance
- At higher energies, may be able to use less expensive systems
  - In particular, use of ILC structures has been discussed

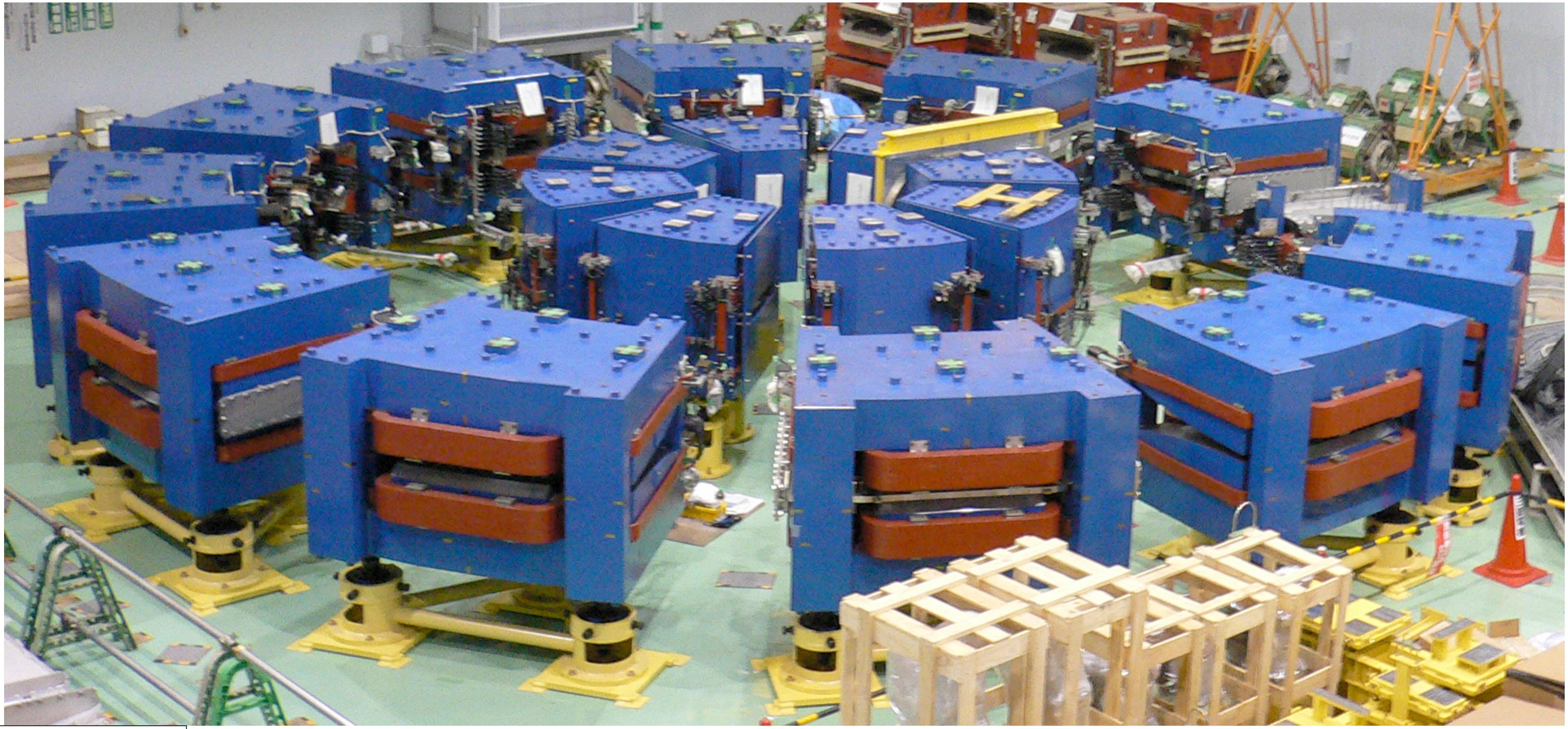
R&D Areas

Outline

- RLA R&D: increasing turns
- FFAG R&D
  - Scaling FFAGs
    - Low frequency FFAG scenario
    - High frequency with harmonic number jump
  - Linear non-scaling FFAGs
    - Time of flight dependence on transverse amplitude
    - Electron model: EMMA
  - Nonlinear non-scaling FFAGs
- Superconducting RF research

FFAG R&D
Scaling FFAGs

- “Scaling” FFAGs: original type of FFAGs, built in the 1950s
- In Japan, scaling FFAGs have been built, under construction



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Scaling FFAGs
Magnet Aperture

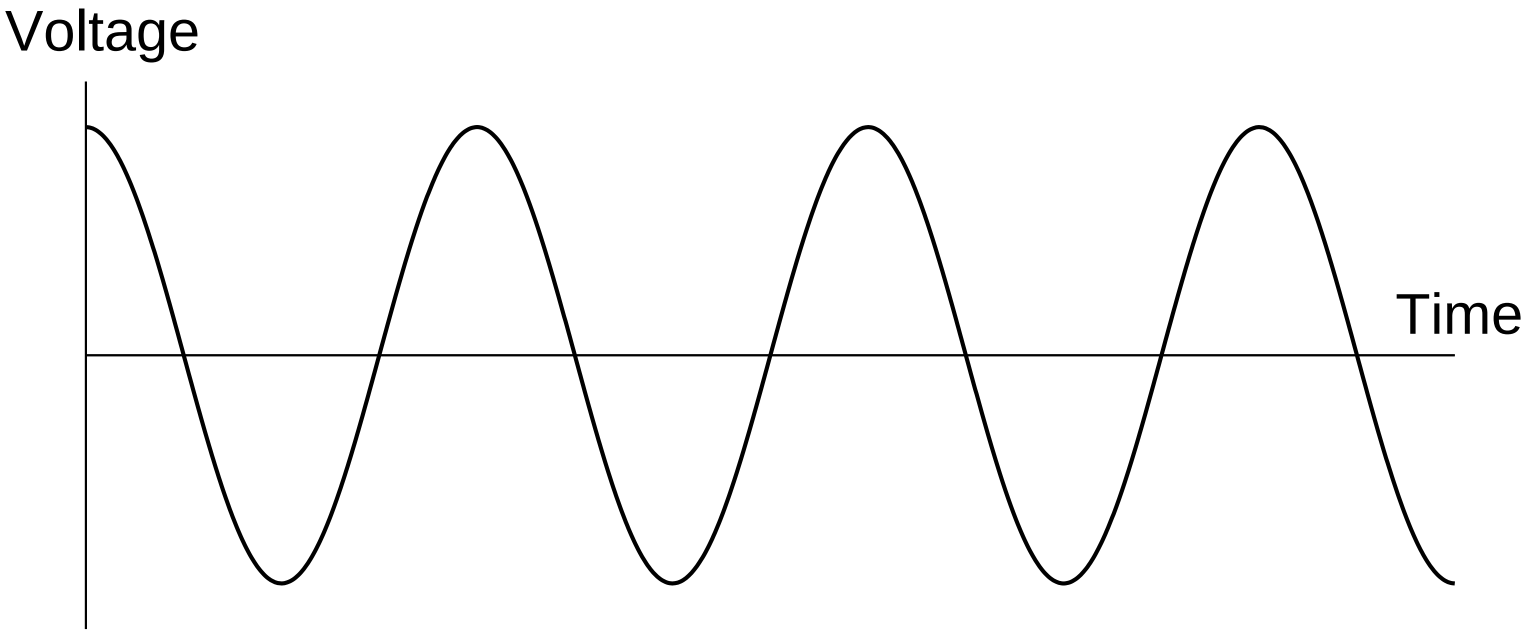
- FFAGs cover a wide range of energies (factor of 2 or more)
- Beam follows different trajectory at different energies
- Forces a wide magnet aperture
- Scaling FFAGs have most of their bending in horizontally focusing magnets
    - Aperture would be smaller if bending were in horizontally defocusing magnets
- Larger apertures become a problem at higher energies, where high-field superconducting magnets are desirable
    - If one can use iron magnets, wide apertures but smaller vertical apertures are cost effective
        - Current research looking at this option for muon acceleration
        - Best at lower energies?

Scaling FFAGs
Time of Flight

- FFAGs cover a wide range of energies (factor of 2 or more) in a single beamline
- Time of flight depends on energy
- Each turn takes a different amount of time

Scaling FFAGs
Time of Flight: Synchronization to RF

- Particles accelerated by RF waveform, prefereably near crest
- Particles are synchronized to RF wave at only one energy
- At other energies (time wrong), will move off the RF crest
- Accelerate in more turns, more turns to move off crest
- Lower RF frequency, longer RF period, can take more turns

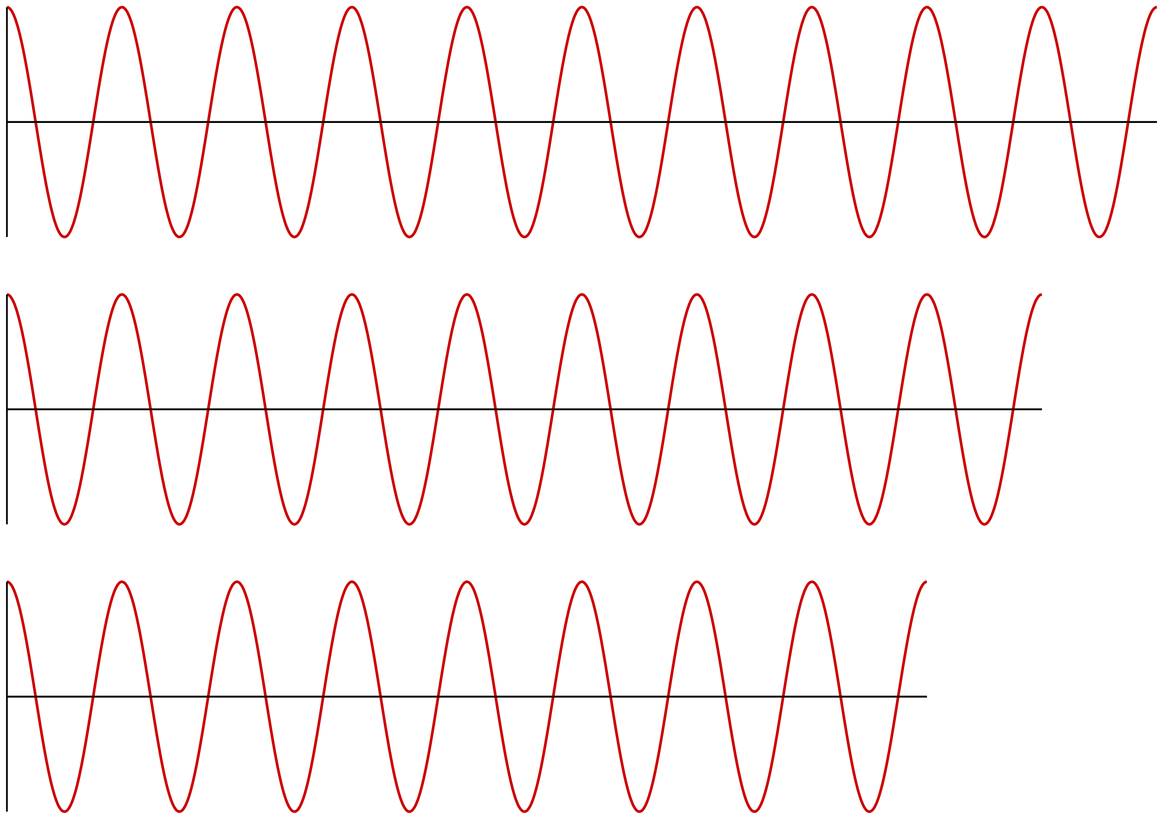


Scaling FFAGs
Low Frequency

- Scaling FFAGs forced to use low frequency (15 MHz range)
  - Low compared to 200 MHz
  - All upstream systems forced down to this frequency
- Gradients are lower than for 200 MHz: more decays
- High peak power requirements for these frequencies
- Important research areas for scaling FFAG use
  - High-gradient, low-frequency RF
  - Ability to rapidly vary cavity frequency with high gradient
- Muon capture slightly less efficient
- Ionization cooling probably not possible: won't work for collider

Scaling FFAGs
Harmonic Number Jump

- Time of flight on each turn is an integer number of RF periods
- That integer can be different on each turn
- Allows the use of high frequency, high-gradient RF



Scaling FFAGs
Harmonic Number Jump R&D Topics

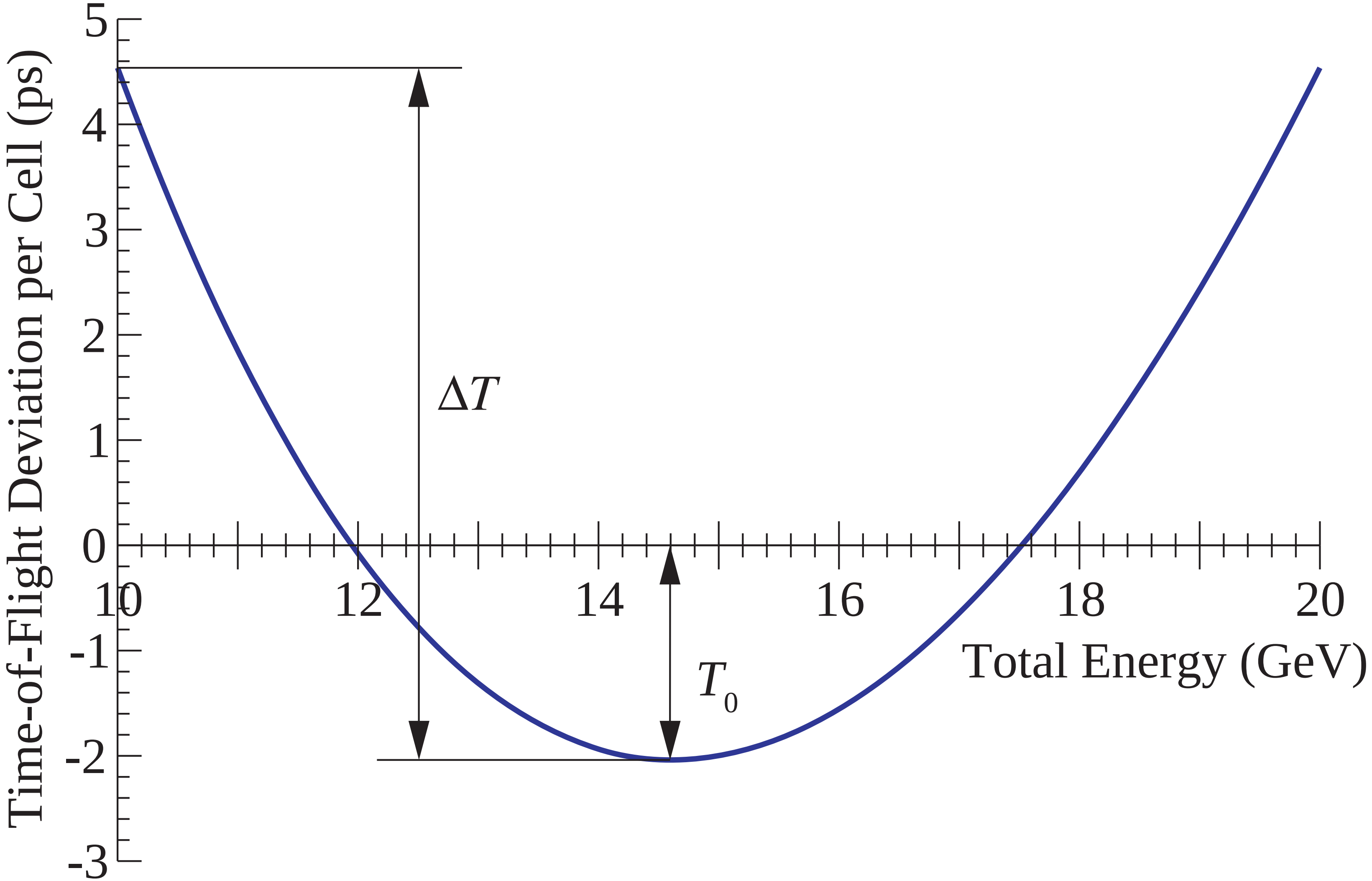
- High frequency fundamental mode cavity too small for wide aperture
  - Use higher order cavity mode: design the cavity
- Requires non-uniform energy gain per turn
  - Design cavity that does this, or
  - Use nearby frequencies to create beat wave (inefficient?)
- Need to fill entire ring with cavities to maintain gradient (decays)
  - One side of ring, period is integer number of RF periods
  - Half turn later, period is half-integer number of RF periods
  - May use beat waves again, or find other methods to address

FFAG R&D

Linear Non-Scaling FFAGs

- Reduce magnet aperture
  - Most bending occurs in horizontally defocusing magnets
- Make time of flight independent of energy for one energy in range
  - Allow the use of higher-frequency RF

Linear Non-Scaling FFAGs
Time of Flight



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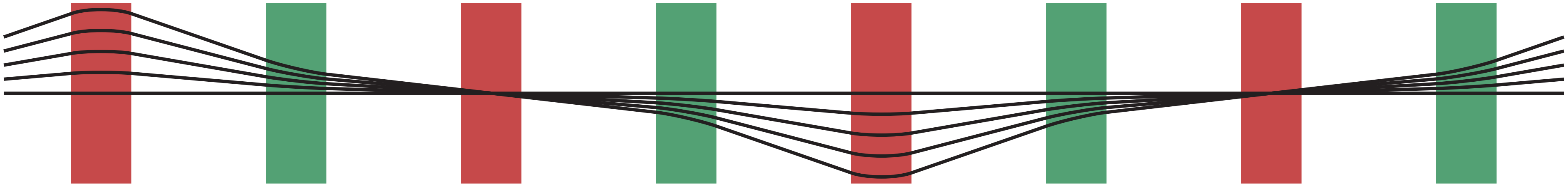
Linear Non-Scaling FFAGs
Design Principles

- Sacrifice: scaling FFAGs have constant tune, avoid resonances. Linear non-scaling FFAGs don't do this.
- Use linear magnets to avoid driving nonlinear resonances
- Maintain symmetry (short, identical cells) to avoid driving linear resonances
  - True for most any FFAG
  - Beware of errors
- Accelerate rapidly through remaining weakly driven resonances
  - Automatic for muons

Linear Non-Scaling FFAGs
Time of Flight Depends on Transverse Amplitude

- As with linac, time of flight depends on transverse amplitude
  - Not a problem in scaling FFAGs: correcting chromaticity fixes the problem
- High amplitude particles arrive late
- To accelerate them, high-amplitude particles should arrive early
- Creates a problem passing beam from one stage to the next
- Problem with a limited phase space that will be accelerated



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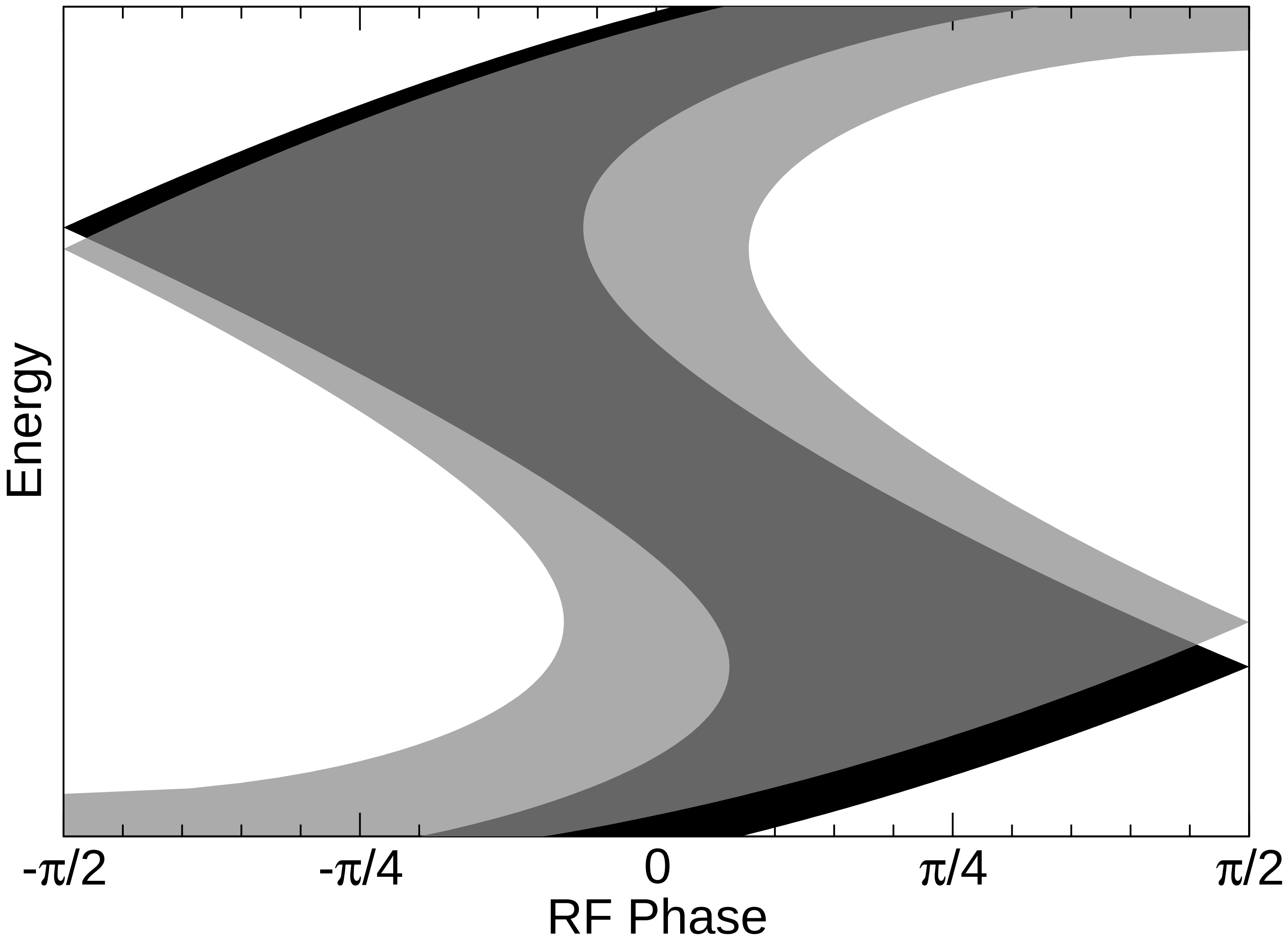
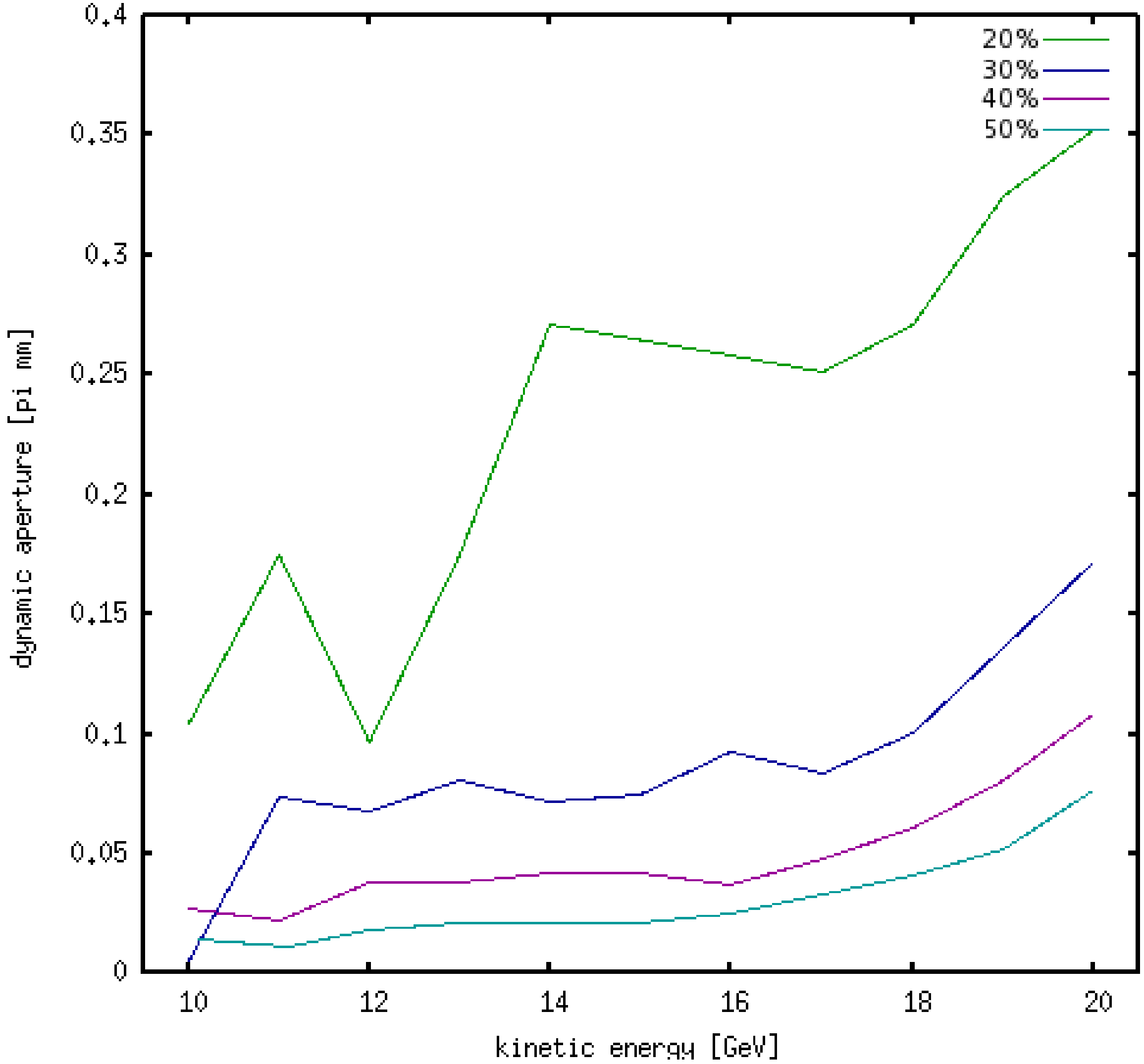
Linear Non-Scaling FFAGs
Long. Phase Space at Different Trans. Amplitudes



Linear Non-Scaling FFAGs
Addressing Time of Flight Problem

- Choose machine parameters optimally to transmit particles at all transverse amplitudes
- Add some sextupoles to correct chromaticity
  - Reduction in dynamic aperture, but some is acceptable
- Add higher RF harmonics
- Increase average RF gradient
  - Add cavities to empty cells
  - Maybe put more cavities per cell
  - Important to have high gradients in the cavities!
  - Reduces number of passes through cavities
- Maybe put positive chromaticity in transfer lines
- Most of this increases cost

Linear Non-Scaling FFAGs
Chromaticity Correction



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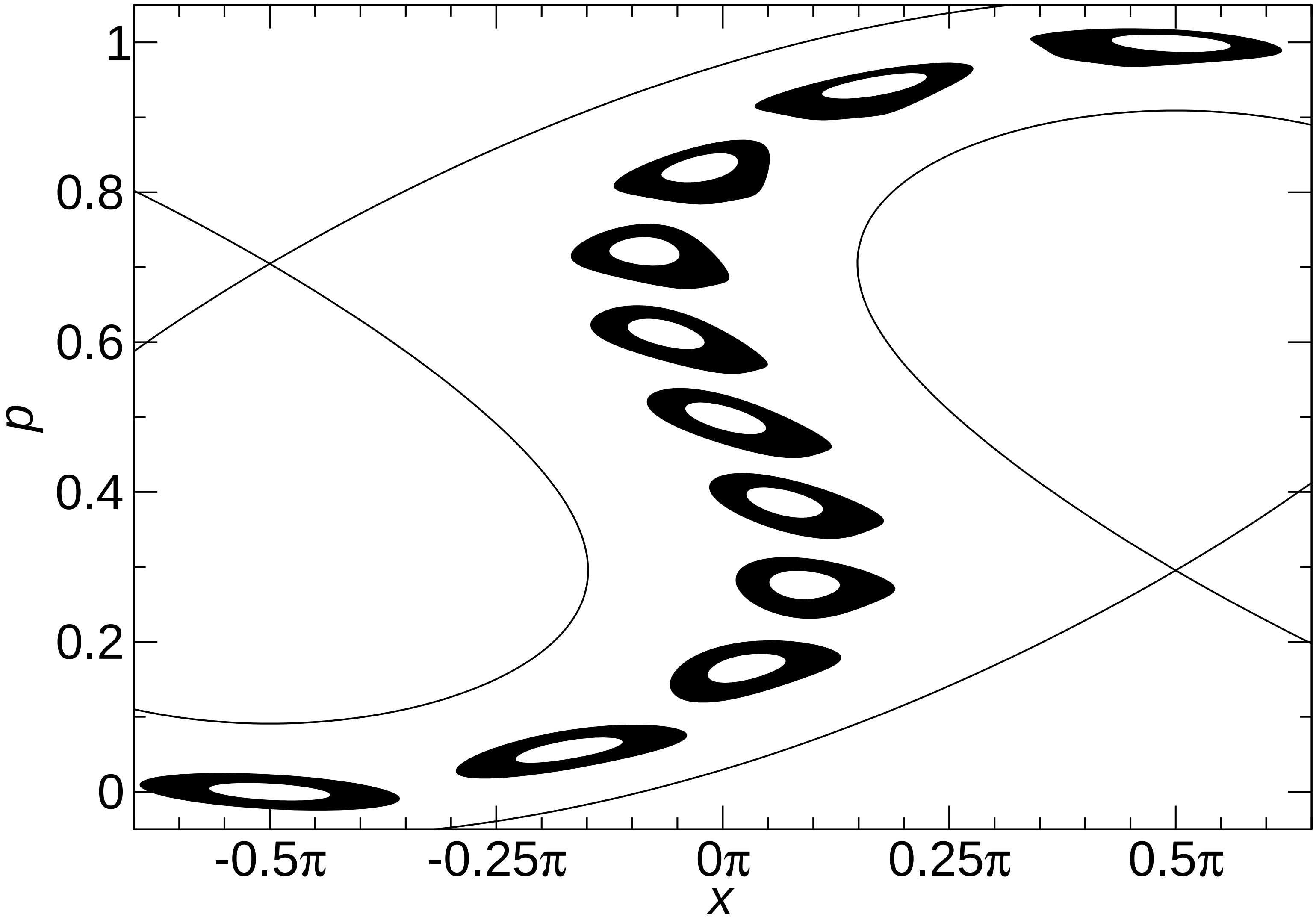
Linear Non-Scaling FFAG Electron Model (EMMA)

- Linear non-scaling FFAG has never been built
- Would like to test whether we understand the dynamics in such a machine
- Build a 10–20 MeV model that accelerates electrons
- Test our understanding of
  - Longitudinal dynamics
  - Transverse dynamics when acelerating through many weak resonances
  - Sensitivity to errors
- In the proposal stages now, sited at Daresbury

Linear Non-Scaling FFAG
Longitudinal Dynamics



Nonlinear Non-Scaling FFAGs

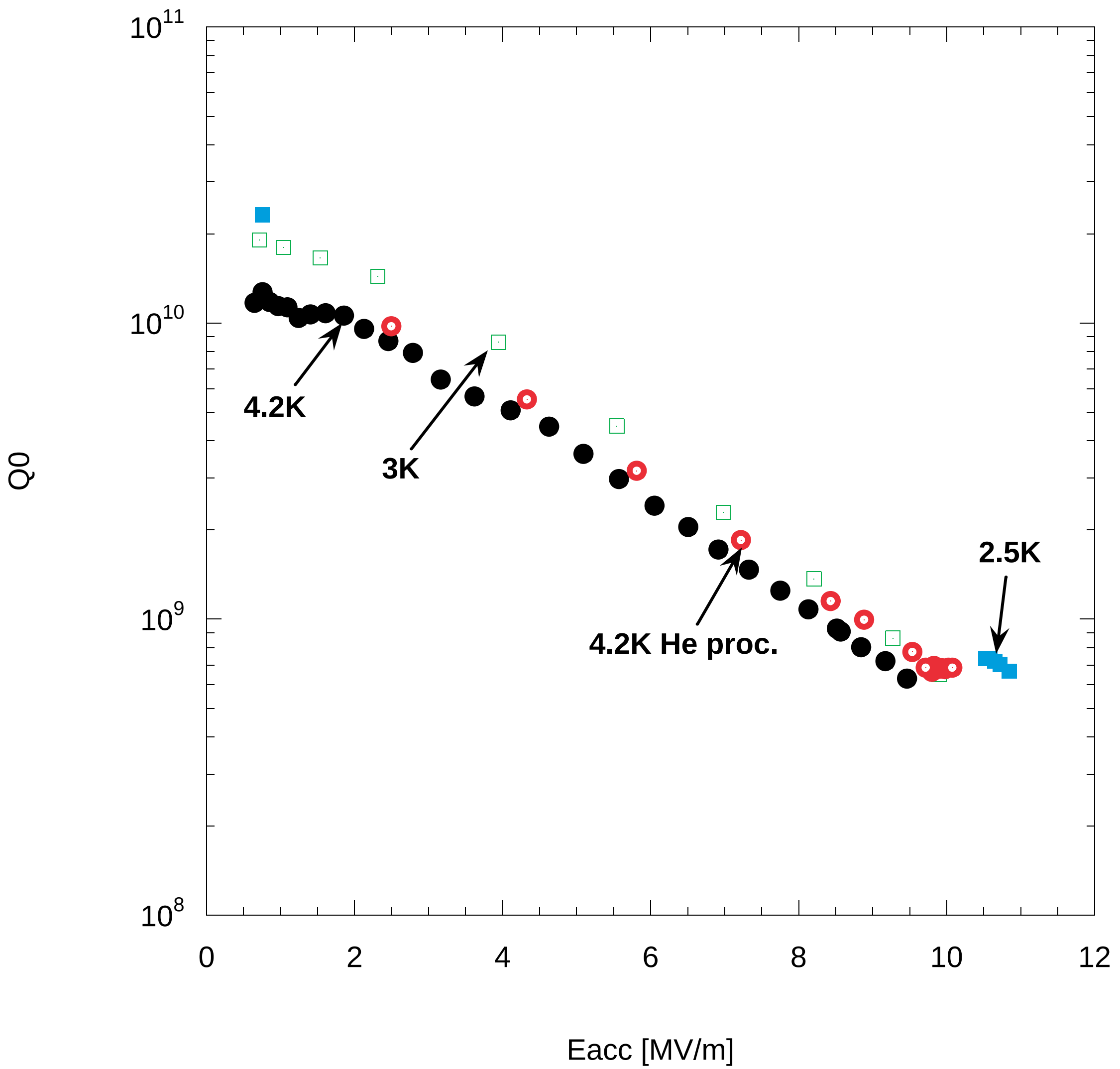
- Try to improve performance of non-scaling FFAGs by using highly nonlinear magnets
  - Reduce time of flight variation with energy
  - Reduce tune variation with energy
    - Hope to improve aperture over scaling FFAGs
- Thus far, transverse dynamic aperture is too low for muons

Superconducting RF R&D

- High gradient important
  - Minimizing muon decay
  - Reduces dynamics problems with FFAGs and linacs
- Use Nb surface on Cu cavities
- 200 MHz cavities built and tested (Cornell, CERN)
  - Sputtered surface: Q-slope very high
- Research ongoing on trying to find better surface (testing on 500 MHz, Cornell, JLab, INFN, ACCEL, others)
  - Explosion-bonded Nb-Cu plates look most promising
- Tested with magnetic field applied after cool down
  - Succeeed to 0.12 T
  - Need to verify this works operationally

Superconducting RF

Q-Slope



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Conclusions

- Acceleration of muons requires a number of different types of subsystems
- Designs driven by avoiding decay, large beam sizes, and reducing costs
- Much R&D is focused on FFAGs
  - Scaling FFAGs: harmonic number jump method looks interesting
  - Linear non-scaling FFAGs: address time of flight problems created by large transverse beam size
- Important to try improving various types of systems: scaling FFAGs, nonlinear non-scaling FFAGs, RLAs. These may later prove to be desirable.
- Obtaining high gradients from lower frequency (200 MHz) superconducting RF is important